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EDWARD L GINZTON LAB OF PHYSICS S E HARRIS ET AL.
15 JUL 85 GL-3891 N00014-84-K-0327

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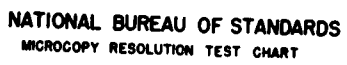
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ANNUAL PROGRESS REPORT
for
JOINT SERVICES ELECTRONICS PROGRAM
Contract N00014-84-K-0327
for the period
1 April 1984 through 31 March 1985
G.L. Report No. 3891

Edward L. Ginzton Labora

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G.L. Report No. 3891

Edward L. Ginzton Laboratory
Stanford University
Stanford, California 94305

Submitted by S.E. Harris on behalf
of the faculty and staff of the
Edward L. Ginzton Laboratory

July 1985

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Submitted by S. E. Harris on behalf on the faculty and staff
of the Edward L. Ginzton Laboratory



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SECTION I

INTRODUCTION

This is the first annual progress report for the JSEP program for the three-year period 1 April 1984 through 31 March 1987 in the Edward L. Ginzton Laboratory at Stanford University. The report covers the period running from 1 April 1984 through 31 March 1985. The research activities during this period were organized into four Work Units:

- Work Unit 85-1. Picosecond Optical Electronic Measurements
(Professor D. M. Bloom)
- Work Unit 85-2. Optical and Nonlinear Optical Studies
of Single-Crystal Fibers
(Professor R. L. Byer)
- Work Unit 85-3. Very High-Frequency Signal Processing Techniques
(Professor G. S. Kino)
- Work Unit 85-4. Metal-Vacuum-Metal Tunneling or Scanned
Tunneling Microscopy
(Professor C. F. Quate)

This has been a particularly exciting year. Key results include the invention, by Professor Bloom, of a particularly simple and elegant electro-optic sampling technique for microwave frequency integrated circuits; continued improvement in the growth of optical fibers by Professor Byer and his students - in particular, the development of a sophisticated, in situ, diameter measurement and control system; the development of very low-loss, high-frequency (8 GHz) transducers by Professor Kino, and the use of these transducers for fiber-optic modulators and taps; and the startling tunneling microscopy imaging of near single atom structure in platinum and silicon by Professor Quate.

Section II of this report summarizes the key accomplishments of this period; Section III presents the annual progress reports for each Work Unit; Section IV lists publications citing JSEP sponsorship;

Section V lists all Ginzton Laboratory reports; and Section VI summarizes our contract and grant support.

SECTION II

REVIEW OF SIGNIFICANT ACCOMPLISHMENTS

A brief review of significant accomplishments during the past year for each of the current Work Units is given in this section. More details of each of these projects will be found in the longer Annual Progress Reports for each of the Work Units, which follow this section.

Work Unit 85-1. Picosecond Optical Electronic Measurements (Professor D. M. Bloom)

In the past year, we have constructed a new electro-optic sampling system suitable for characterizing monolithic microwave integrated circuits in a noninvasive manner. A unique aspect of this sampling system is the electronic synchronization technique employed to synchronize the mode-locked laser pulses to the microwave source which drives the circuit under test. Using this system, a 2-12 GHz distributed amplifier was characterized.

Work Unit 85-2. Optical and Nonlinear Optical Studies of Single-Crystal Fibers (Professor R. L. Byer)

In the second year of its operation, the single-crystal fiber growth apparatus has produced over 400 fibers of sapphire, ruby, and LiNbO_3 , in addition to several new materials. The growth station has proven to be easy to use, and a more thorough understanding of the process of laser-heated miniature pedestal crystal growth has been obtained.

The installation of the real-time in situ diameter measurement system has enabled the feedback-controlled growth of fibers with a factor of 10 better diameter stability than open-loop grown fibers. The measured surface scattering loss of such fibers is as low as 0.01 dB/cm. Besides the growth of smooth, low-loss fibers, this system also has

enabled us to identify sources of diameter variations and will lead to the design of an even better feedback controller.

Improved monolithic ruby fiber lasers and the first monolithic Nd:YAG fiber lasers have been demonstrated. Contributing to the improved performance of these devices were better end-face polishing methods and the much greater diameter stability of the fibers. The effects of imperfections in the end-face polishing on fiber laser action have been theoretically modeled.

Work Unit 85-3. Very High-Frequency Signal Processing Techniques
(Professor G. S. Kino)

High-quality, low-loss 8 GHz transducers can now be made routinely in our laboratory. For the first time we have been able to pass 7 GHz acoustic waves through a Hertzian contact with very low loss. We have developed a 4 GHz fiber-optic acoustic modulator which is beginning to show encouraging results.

Work Unit 85-4. Metal-Vacuum-Metal Tunneling or Scanned
Tunneling Microscopy
(Professor C. F. Quate)

During this period we have been successful in recording high resolution images of atomic structure in both [111] platinum and [100] silicon. Our images show the atomic positions in two dimensions. This is the first time the atomic positions have been imaged on [100] silicon. On that face the distance between atoms is less than it is on the [111] reconstructed face. This was made possible by our advanced design of the walker and scanning device. It is also notable that our images are recorded in seconds rather than minutes.

SECTION III
ANNUAL PROGRESS REPORTS

Unit 85-1

PICOSECOND OPTICAL ELECTRONIC MEASUREMENTS

D. M. Bloom
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A. INTRODUCTION AND OBJECTIVES

Our efforts on this contract have been aimed at significantly improving the state of the art of ultrafast electronic measurements. These efforts have used an ultra-short-pulse laser to probe integrated circuit signals noninvasively.

Efforts to advance the speed of analog and digital electronics are limited as much by the inability to make accurate high-speed measurements as by the devices themselves. Originally we proposed to construct an electro-optic sampling system of the Valdmanis-Mourou type that utilized a separate electro-optic crystal bonded to the device under test in a hybrid assembly. However, prior to the start of this contract, we invented an important new technique which allows GaAs integrated circuits to be probed internally via the electro-optic effect of GaAs itself. Over the past year we have refined this new technique and have begun to apply it to the study of monolithic microwave integrated circuits (MMIC's).

B. PROGRESS AND ACCOMPLISHMENTS

Over the past year we have constructed an electro-optic sampling system suitable for probing monolithic microwave integrated circuits.

With this system, we have begun to study the performance of a traveling wave amplifier obtained from Varian Associates. This circuit uses four GaAs MESFET's as distributed amplifier elements to provide gain from 2-12 GHz.

Electro-optic sampling of high-speed electronics is motivated by the ability of laser systems to produce ultrashort light pulses and then, through the electro-optic effect, sense electrical waveforms. The electric field of an applied signal in an electro-optic crystal induces a birefringence which causes a polarization change to incident light. When the phase modulated light passes through an analyzing polarizer, the resulting amplitude modulation is proportional to the applied electric field for signals much smaller than the switching voltage (typically many kilovolts). In these experiments, the GaAs substrate of the circuits also acts as the electro-optic crystal to modulate the light. A longitudinal sampling geometry (Fig. 1) is used to probe microstrip-line voltages on <100> cut GaAs (the most common orientation for monolithic microwave integrated circuits).

Initial demonstrations of electro-optic sampling and of direct electro-optic sampling in GaAs used a pump-probe technique, where the measured impulse response was excited with fast photo-devices, triggered from a portion of the same light beam providing the sampling pulses. However, since the electro-optic effect provides a signal proportional to the product of the intensity of the sampling light and the electric fields in the dielectric, the sampler acts in the frequency domain as a wideband mixer. The laser output, a train of short pulses in time, is a pulse train in frequency space as well, with the harmonics spaced by the fundamental mode-locking repetition rate. Microwave signals exciting the device under study then mix with the harmonics of the mode-locked

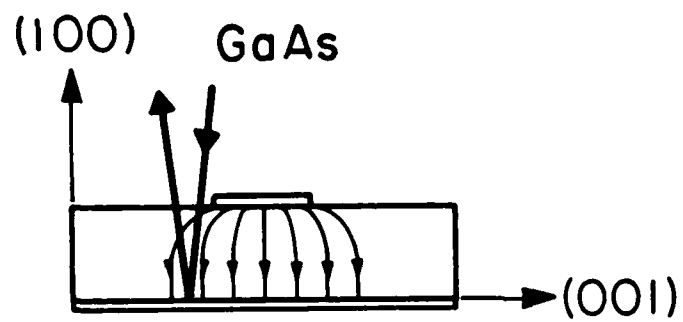


Fig. 1. Electro-optic sampling geometry for GaAs microstrip transmission line.

laser to produce sum and difference components around each harmonic. The mixer product between the microwave signal and the nearest laser harmonic will produce a signal between dc and half the fundamental mode-locking rate of the laser, where one can detect the signal with a conventional silicon photodiode.

If the microwave synthesizer and the signal generator driving the mode-locker of the laser are phase-locked, the microwave signal can be tuned to an exact harmonic $N \cdot f_0$, where N is the harmonic number and f_0 is the mode-locker frequency, of the laser spectrum with a resulting mixer product at dc. In the time domain this corresponds to sampling the sinusoidal wave at the same point every N^{th} cycle. The phase of the MW signal can then be varied with respect to the sampling pulse train to map out the waveform.

The sampling system consists of a commercially available mode-locked Nd:YAG laser producing $1.06 \mu\text{m}$, 100 ps pulses at an 82 MHz rate. A fiber-grating pulse compressor shortens the pulses to 10 ps, increasing the sampler bandwidth. The beam is focused next to a transmission line on the traveling wave amplifier. The light is reflected off the metallized backside of the substrate, collected and recollimated with the focusing lens, and directed through an analyzing polarizer onto a photodiode. A spectrum analyzer acts as a fixed frequency receiver to display the waveform.

A key aspect of this type of measurement is the timing jitter or phase noise of the laser. The phase noise of many commercial microwave synthesizers corresponds to timing jitter of less than a picosecond. However, initial phase noise measurements indicate timing jitter on the order of 10 ps rms arising from the laser system. To combat this noise, a phase-lock-loop was implemented around the laser, reducing the timing

jitter to 2 ps rms and providing a phase reference for relative phase measurements and signal averaging.

Figure 2 shows gain as a function of frequency, measured with the sampler and with commercial electronics. The light beam was placed at the input (gate) transmission line and the amplitude of the mixer product was measured for frequencies corresponding to a mixer IF of 10 MHz. The same data was then taken with the sampler positioned at the output (drain) transmission line, and the resulting gain plotted in Fig. 2. Since the sampler bandwidth is large enough to include harmonics of signals in the device's operating range, waveforms with distortion can be detected. Figure 3 shows distortion deliberately introduced by varying the device's dc bias. By lowering the drain-source bias voltage the gain is reduced and clipping is observed on the one side of the waveform. Other measurements have observed forward gate conduction from overdriving the input and variation of the amplitude and phase of the signals at separate FET outputs along the amplifier.

In conclusion, the electro-optic sampler provides non-contact, non-invasive signal measurements for high-frequency circuits and devices. Since 1.06 μm optical pulses as short as 1 ps and laser timing jitter as small as 2 ps have been demonstrated, the potential bandwidth of the system is several hundred gigahertz. This sampling technique is adaptable to many high-frequency measurements, is not limited to the transmission line reflection geometry, and has application to both analog and digital circuits. Since vector measurements are possible, this technique forms the basis for noninvasive wideband network analysis.

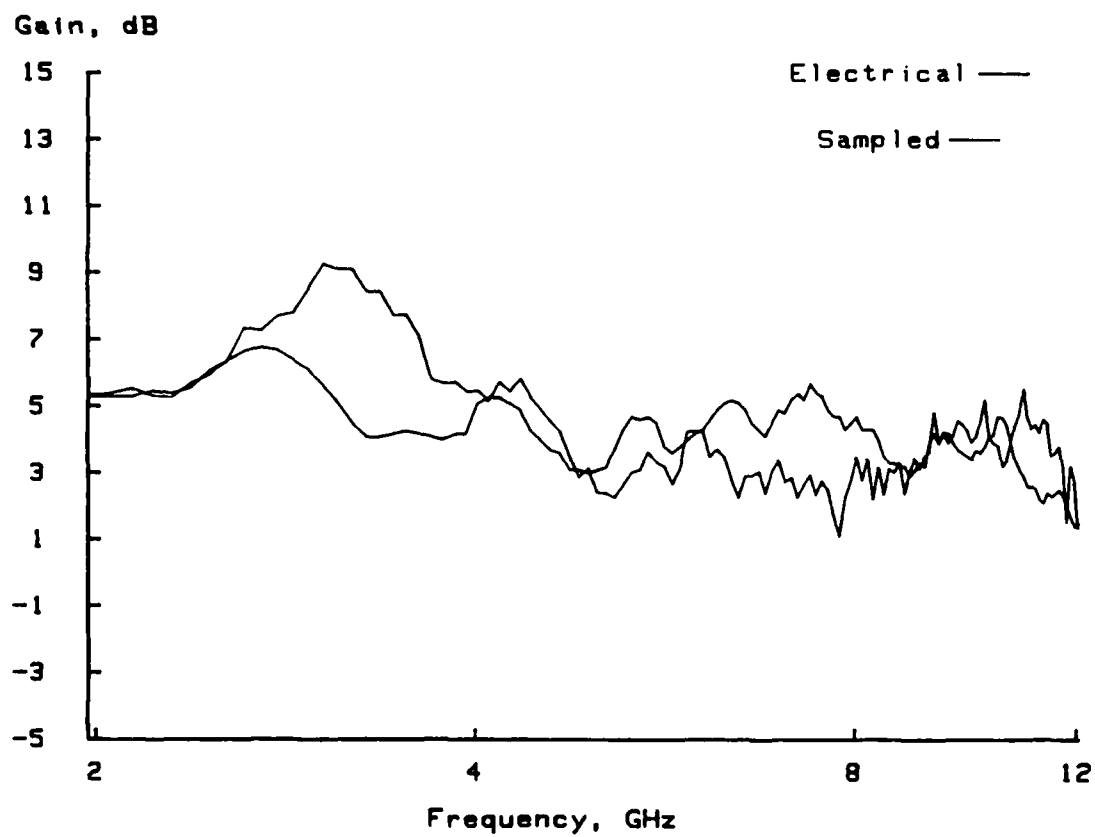
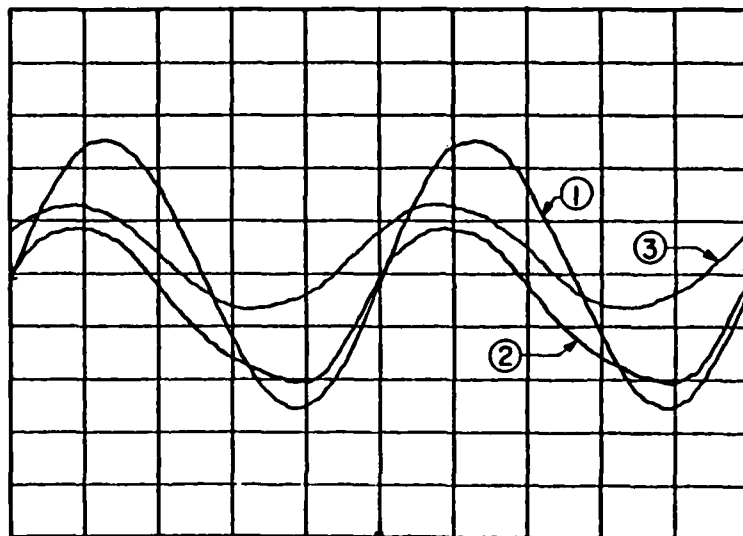


Fig. 2. Traveling-wave amplifier gain versus frequency.

Operating frequency = 4.09 GHz
(50th laser harmonic)

- ① Saturation region
($V_{ds} = 3 \text{ V}$
 $V_{gs} = 0 \text{ V}$)
- ② Triode region
($V_{ds} = 1 \text{ V}$
 $V_{gs} = 0 \text{ V}$)
- ③ Pinchoff
($V_{ds} = 3 \text{ V}$
 $V_{gs} = -2 \text{ V}$)



50 ps per division

Fig. 3. Synchronous sampling of an externally driven
2 to 12 GHz GaAs FET traveling-wave amplifier.

C. PUBLICATIONS, INVITED PAPERS, ORAL DISCLOSURES, PATENTS, AND
HONORS/AWARDS/PRIZES

1. Publications

B. H. Kolner, J. D. Kafka, D. M. Bloom, and T. M. Baer, "Compression of Mode-Locked Nd:YAG Pulses to 1.8 ps," in Proceedings of the Topical Meeting on Ultrafast Phenomena (Berlin: Springer-Verlag, 1984).

B. H. Kolner and D. M. Bloom, "Direct Electro-Optic Sampling of Transmission Line Signals Propagating on a GaAs Substrate," Elect. Lett. 20, 818 (September 1984).

J. D. Kafka, B. H. Kolner, T. M. Baer, and D. M. Bloom, "Compression of Pulses from a CW Mode-Locked Nd:YAG Laser," Opt. Lett. 9, 505 (November 1984).

B. H. Kolner, K. J. Weingarten, and D. M. Bloom, "Electro-Optic Sampler for Gallium Arsenide Integrated Circuits," SPIE Proc. 533, 139 (January 1985).

B. H. Kolner, K. J. Weingarten, M. J. W. Rodwell, and D. M. Bloom, "Electro-Optic Sampling and Harmonic Mixing in GaAs," in Proceedings of the Picosecond Electronics and Optoelectronics Meeting (Berlin: Springer-Verlag, 1985) (to be published).

2. Invited Papers

"Electro-Optic Sampler for Gallium Arsenide Integrated Circuits," SPIE Meeting on Ultrashort Pulse Spectroscopy and Applications, Los Angeles, CA (January 22, 1985).

"Picosecond Optical Electronics," Eighth Conference on Optical Fiber Communication, San Diego, CA (February 12, 1985).

3. Oral Disclosures

"Compression of Nd:YAG Pulses to 1.8 Picoseconds," Topical Meeting on Ultrafast Phenomena, Monterey, CA (June 14, 1984).

"Compression of CW Mode-Locked Nd:YAG Pulses," International Quantum Electronics Conference, Anaheim, CA (June 21, 1984).

"Picosecond Optical Electronic Measurements," Tektronix, Inc., Beaverton, OR (October 18, 1984).

"Picosecond Optical Electronics," Stanford Center for Integrated Systems, Stanford University, Stanford, CA (November 7, 1984).

"Picosecond Electro-Optic Sampling and Harmonic Mixing in GaAs," Picosecond Electronics and Optoelectronics Conference, Incline Village, NV (March 13, 1985).

4. Patents

David M. Bloom and Brian H. Kolner, "High Speed Testing of Electronic Circuits," U.S. Serial #648,456 (September 7, 1984).

5. Honors/Awards/Prizes

None

Unit 85-2

OPTICAL AND NONLINEAR OPTICAL STUDIES
OF SINGLE-CRYSTAL FIBERS

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A. INTRODUCTION AND OBJECTIVES

The growth of crystalline materials in fiber optical form makes possible a wide variety of devices which will be useful in the generation and processing of light and which will couple well to the glass fibers used for transmission. Optical fibers can be made from materials which can withstand more adverse conditions than glass fibers. Nonlinear optical processes can operate more efficiently in a waveguide because confinement provides high optical intensities over long interaction lengths, a combination which is not available in bulk crystals due to diffraction. Crystalline lasers and modulators can be made, as well as passive components such as polarizers, isolators, and filters. Our objectives, then, are to learn to grow, fabricate, and characterize single-crystal fiber devices.

An apparatus to produce optical-quality single-crystal fibers using the laser-heated miniature pedestal growth technique has been built at Stanford and, in its second year of operation, has produced over 400 fibers of a variety of materials. We have concentrated on the materials sapphire (Al_2O_3), ruby ($\text{Cr}:\text{Al}_2\text{O}_3$) and Nd:YAG, and LiNbO_3 , which are representative, respectively, of the passive, active, and nonlinear classes of possible single-crystal fiber applications.

In all the applications, it is necessary to grow smooth fibers with minimal fluctuations in diameter. Diameter ripples on the order of a few percent of the mean diameter can cause the loss of light out of the

fiber by scattering into radiation modes. Fluctuations on the order of a few tenths of a percent can cause reduction in the efficiency of nonlinear interactions because, while scattering out of the fiber may be small, scattering out of desired guided modes and into other, non-phase-matched guided modes can occur. Thus, a major thrust of our effort has been in the improvement of the diameter stability of the fibers.

The growth of high-quality fibers is only the first step toward the production of useful devices. All fiber devices require properly polished end faces. Ferroelectric materials must be "poled," or made to contain a single domain or other desirable domain structure. A method for cladding the fibers must be found to reduce the core size and protect the refractive index interface. Methods must be developed to characterize properties of the fibers at the various stages of fabrication and the performance of completed devices. Our research program addresses all of these issues, and significant progress has been made on every front in the past year.

B. PROGRESS AND ACCOMPLISHMENTS

1. Growth Station

In the past year over 400 fibers have been grown of sapphire, ruby, Nd:YAG, and LiNbO_3 . In addition, some new materials have been grown for the first time in fiber form. The growth station has proven to be straightforward to operate, and currently eleven students in three different research groups are qualified to grow fibers.

Improvements to the growth station enclosure have been made which have provided better sealing of the growth from ambient air currents and at the same time have allowed the installation of the real-time diameter measurement system.

The diameter measurement system (a paper on which will be published in the August 1st issue of Applied Optics) can measure the diameter of fibers as they are grown to a diameter accuracy of 0.01%, at a measurement rate of 1 kHz, with an axial resolution of 6 μm , and with a working distance of 160 mm. This capability has made possible the closed-loop control of the fiber diameter during growth. Sapphire fibers with a diameter stability of $< 0.2\%$ rms (around a mean diameter of 150 μm) have been grown using a simple analog proportional controller which feeds back to the fiber pull motor speed. This is a factor of 10 improvement over a typical open-loop fiber grown under otherwise identical conditions. Nd:YAG fibers of 50 μm diameter have been grown with $< 0.5\%$ rms fluctuations. Besides growing the smoothest single-crystal fibers to date, the in situ measurement of the diameter has also made possible the identification of noise sources which cause diameter variations. It appears that power fluctuations of the CO_2 laser used to melt the source material are now the major source of residual noise. A paper was presented at CLEO '85 on the controlled growth of single-crystal fibers.

The high-speed limit on the growth rate of single-crystal fibers has been explored. One essential limit in pull rate is the formation of "microvoids," which look like microscopic bubbles in the fiber. The onset of microvoid formation has been studied in sapphire and ruby at different chromium doping levels, and in different fiber sizes. The work is reported in the Ph.D. dissertation of John Nightingale.

Scanning electron microscopy has revealed the occasional presence of fine-scale surface ripples on the fibers. Although generally absent, these ripples are sometimes visible under the proper illumination conditions; they have a height of $< 0.1 \mu\text{m}$, and a period which depends on the

growth speed. Their origin is not well understood, but it is unlikely that they will present any problems in the making of devices.

2. Materials and Devices

In addition to the "traditional" materials (sapphire, ruby, Nd:YAG, and LiNbO_3), several new materials were grown for the first time last year. They include terbium gallium garnet (TGG), a magneto-optic material suitable for use in fiber Faraday isolators; potassium niobate (KNbO_3), a nonlinear material useful for near-room temperature frequency-doubling of GaAlAs diode laser light; and Nd: LiNbO_3 , a laser material which could also frequency-double its own light in a single fiber.

Studies have been made on doping the tips of sapphire fibers with Fe, Cu, Ni, and Cr to form blackbody radiators for use in a sapphire fiber thermometer. The preliminary results show that Cr doping is the most promising for this application.

The first monolithic single-crystal fiber device to be demonstrated was a fiber ruby laser, reported last year. Improvements were made this past year in the areas of polishing and coating the end faces with dielectric mirrors. In addition, a theory modeling the effects of edge chipping, tilt, and curvature of the mirror surfaces on fiber laser cavity losses has been developed. Progress on ruby fiber lasers is reported in a paper which has been submitted to Applied Optics. This work and additional results on new monolithic Nd:YAG fiber lasers (which should have lower waveguide losses, since they were made using the new diameter-controlled fibers) were also reported in a poster presentation at CLEO '85.

The first step toward nonlinear fiber devices has been made with the second harmonic generation of $1.06 \mu\text{m}$ radiation in a $\text{Mg}:\text{LiNbO}_3$ sample

grown on the fiber machine. This interaction was unguided, but it showed that the composition of the material was the same as the source material within experimental error, and reasonably homogeneous over the length of the sample. This information is essential in order to predict phasematching temperatures and to reassure us that the material we grow is exactly what we think we have.

3. Fabrication and Characterization

In the course of fiber laser experiments it proved necessary to develop an improved polishing technique for fiber ends in order to assure the flatness of the mirror faces and their perpendicularity to the fiber axis. This was accomplished by making fixtures of the same crystalline material as the fiber. The fibers are held by clamping them in grooves in the jig, in which they are cushioned by evaporated layers of gold. The absence of organic materials such as epoxies allows the fiber ends to be coated while the fibers remain in the same fixture in which they were polished.

Much work has been done on proton exchange in LiNbO_3 , which changes the refractive indices, and is therefore useful for making waveguides. The diffusion properties of protons into photorefractive damage-resistant Mg:LiNbO_3 have been studied by making slab waveguides. (Protons raise n_e , allowing slab waveguides to be made for this polarization, whereas they lower n_o , allowing this polarization to be guided in fibers.) The refractive index profiles can be found by observing the angles at which various modes couple into and out of a waveguide. Using this data, a computer model for the nonlinear diffusion process has been developed. A poster paper was presented at CLEO '85 on this work. The first clad c-axis LiNbO_3 fiber has been shown to exhibit very good low-order mode propagation without coupling to high-order modes, although the guide is

still highly multimode (approximately 100 μm diameter). This result is very encouraging for LiNbO_3 device development. It should be noted that since only one index is clad, only one polarization is guided in this fiber, making it a device - a fiber polarizer - without further processing.

Measurements on the surface scattering losses from sapphire fibers grown with and without feedback control of the diameter have been made, and were reported at CLEO '85. These measurements were made with a specially-developed integrating sphere apparatus. We thus now have an additional characterization tool which will be useful in the development of all types of fiber devices. For a factor of 10 diameter stability improvement in 150 μm diameter fibers, we have improved the scattering losses at $\lambda = 632.8 \text{ nm}$ by a factor of 2 to a loss of only 0.01 dB/cm (or 0.2%/cm).

4. Continuing Research

In the coming year of this contract, we will be growing new materials which may be of interest in nonlinear devices. The materials we are interested in trying include $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$ (for frequency doubling), BaTiO_3 (which is electro-optic and photorefractive), and more KNbO_3 . These materials share the problem of strain-changing phase transitions while cooling, a problem which should be less serious in fiber form than in the bulk. We may also repeat the growth of Li_2GeO_3 , a good stimulated Raman material, since there is some interest in generating 1.4 μm light as a pump source for the Raman amplification of solitons in glass fibers.

The problem of poling ferroelectric materials will soon need more attention, since after our first electro-optic device, which will use a c-axis LiNbO_3 fiber which fortuitously grows single-domain, we will need a-axis fibers for nonlinear devices.

We also expect to pursue alternative diffused-cladding approaches, such as the diffusion of tantalum or MgO into LiNbO_3 , in addition to further proton diffusion experiments. This is because both indices must be lowered in order to guide two polarizations in a nonlinear device and, as mentioned before, while proton exchange lowers one index, it raises the other.

We expect to produce the first nonlinear devices this year. The potentials for passive devices, however, have not been exhausted. The controlled growth of fibers has enabled the intentional modulation of fiber diameters at high enough spatial frequencies (5 μm period so far) to make Bragg filters or reflectors in fibers a possibility, and we may use that capability to demonstrate new passive devices in sapphire.

Finally, since dye-laser pumped Nd:YAG oscillation has been seen, the short step to a truly practical device can soon be made by simply diode-pumping Nd:YAG lasers.

It is easy to see that the capabilities in optical-quality fiber growth, fabrication, and characterization we have developed during the past year have made possible the growth of more materials and the production of more kinds of devices than we have the manpower to investigate.

C. PUBLICATIONS, INVITED PAPERS, ORAL DISCLOSURES, PATENTS, AND
HONORS/AWARDS/PRIZES

1. Publications

M. Fejer, J. Nightingale, G. Magel, and R. Byer, "Laser Assisted Growth of Optical Quality Single Crystal Fibers," SPIE Proc. 460, 26 (1984).

M. M. Fejer, J. L. Nightingale, G. A. Magel, and R. L. Byer, "Laser-Heated Miniature Pedestal Growth Apparatus for Single-Crystal Optical Fibers," Rev. Sci. Instr. 55, 1791 (1984).

M. Dignonnet, M. Fejer, and R. Byer, "Characterization of Proton-Exchanged Waveguides in $\text{MgO}:\text{LiNbO}_3$," Opt. Lett. 10, 235 (1985).

M. M. Fejer, G. A. Magel, and R. L. Byer, "High-Speed High-Resolution Fiber Diameter Variation Measurement System," Appl. Opt. (to be published).

J. L. Nightingale and R. L. Byer, "A Guided-Wave Monolithic-Resonator Ruby Fiber Laser," Appl. Opt. (submitted for publication).

2. Invited Papers

"Single Crystal Fibers," Japanese Opto-Electronic Association Meeting, Tokyo, Japan (January 25, 1985).

3. Oral Disclosures

"Nonlinear Interactions in Single Crystal Fibers," NASA Workshop on Tunable Solid State Lasers for Sensing, Menlo Park, CA (October 1-3, 1984).

"Monolithic Resonator Single Crystal Fiber Laser," Paper WM36, Conference on Lasers and Electro-Optics, Baltimore, MD (May 21-24, 1985).

"Single Crystal Fiber Research," University of Osaka, Osaka, Japan (January 28, 1985).

"Controlled Growth of Single Crystal Optical Fibers," Paper ThH2, Conference on Lasers and Electro-Optics, Baltimore, MD (May 21-24, 1985).

"Proton-Exchanged Waveguides in $\text{MgO}:\text{LiNbO}_3$," Paper ThM45, Conference on Lasers and Electro-Optics, Baltimore, MD (May 21-24, 1985).

4. Patents

J. L. Nightingale, M. M. Fejer, and R. L. Byer, "Fiber Translation System for Crystal Fiber Growth," U.S. Serial #645,839 (August 31, 1984).

M. M. Fejer, G. A. Magel, and R. L. Byer, "Method and Means for High Resolution Measurements of Fiber Diameter," U.S. Serial #06/648,454 (September 7, 1984).

5. Honors/Awards/Prizes

John L. Nightingale received a Newport Research Award from the Optical Society of America for the 1984-85 academic year. This award is made to doctoral candidates who are pursuing thesis projects in lasers and electro-optics.

Unit 85-3

VERY HIGH-FREQUENCY SIGNAL PROCESSING TECHNIQUES

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A. INTRODUCTION AND OBJECTIVES

It is the aim of this program to examine new acoustic wave techniques for use at very high frequencies in the range of several GHz. We are interested in employing very high-frequency acoustic waves for signal processing of the type typically carried out with surface acoustic wave devices in the UHF range. Our basic objectives are to construct an acoustic convolver operating at an input frequency of 5.5 GHz, and to construct fiber-optic acoustic modulators and external tapping devices, which will open up a wide range of new possibilities for signal processing at very high frequencies.

B. PROGRESS AND ACCOMPLISHMENTS

During the past year we have built several new prototypes of high-frequency devices. One result of this work has been an improvement in reliability and speed of our zinc oxide transducer fabrication process. We have developed new magnetron sputtering techniques employing an argon-oxygen atmosphere which enable us to obtain high-quality zinc oxide films at relatively low substrate temperatures of the order of 100°C. We are also employing our older sputtering technique in pure oxygen. With it, we have constructed 8 GHz transducers with only a few dB conversion loss.

We are interested in nondestructive testing with very high-frequency acoustic waves. We are also interested in constructing very high-

frequency transducers which can be placed in contact with a single-mode optical fiber to modulate an optical wave passing through it. In both cases, we need to construct a high-frequency transducer on a buffer rod which can be placed in contact with the material of interest, and allow acoustic waves to pass with little loss through the contact. For this purpose, we have constructed a 7 GHz ZnO transducer on a sapphire buffer rod which has its opposite surface lapped to a radius of 20 cm. When placed in contact with a flat sapphire plate, a Hertzian contact of 100-200 μm diameter is formed. The diameter of this contact was more than sufficient to allow passage of the 40 μm diameter acoustic beam. We worked out new techniques to align this contact with the transducer, and were able to excite an acoustic wave in the sapphire plate and observe multiple reflections of a 7 GHz tone burst within the plate. The loss through the contact was only of the order of 1.2 dB.

Much of our effort has gone toward developing an acousto-optic tap for an optical fiber. A method to tap out a small fraction of the light guided by a single-mode fiber at high bandwidths would be useful for wideband signal processing. It would also make it possible to construct switchable taps and high-frequency modulators for optical fibers. These are all very important goals which, if realized, would open up entirely new techniques for signal processing.

A commonly used technique uses a Ti-diffused LiNbO_3 waveguide. The method we will now describe has important differences. For example, the system employs a single-mode optical fiber rather than a thin film waveguide, and it uses a Bragg interaction mode; hence, the tapped light will be frequency shifted.

Since we have learned how to use a Hertzian contact to excite an acoustic wave in a crystal, our fiber-optic tap takes advantage of this

ability to avoid the problems associated with building an acoustic transducer directly on a fiber. YAG crystals with zinc oxide transducers, illustrated in Fig. 1, have been successfully fabricated and tested. The spherical face of the YAG crystal is pressed against the flat of a D-shaped fiber to form a Hertzian contact. An acoustic wave travels from the input transducer through the contact and the fiber core. When the angle and frequency of the wave satisfy the Bragg condition, light is scattered upward through the YAG crystal where it can be collected and detected by a photodiode. An output transducer in the shape of a grating with a sidelobe phase matched to the reflected acoustic wave allows the reflected power to be monitored. The alignment of the YAG crystal relative to the fiber is adjusted until the reflected power drops, indicating the acoustic wave is being coupled into the fiber. This allows the pieces to be aligned acoustically before putting light into the fiber.

We now have YAG crystals with 4.1 GHz transducers and we have brought them into good acoustic contact with a single-mode optical fiber. We have clearly observed light scattered out of the fiber by the acoustic wave, and have modulated the light by means of the applied rf signal. The next step is to better characterize the effect and, if possible, enhance it.

Our work on bulk wave convolvers continues, but, as before, the construction of these convolvers is hindered by the need to sputter films on four faces of a LiNbO_3 crystal and the need to locate acoustic transducers in good alignment very close to an edge of the crystal. Transducer alignment has been improved by grinding each crystal to an extremely close angular tolerance and locating the transducer relative to the accurate crystal edges. To deposit a transducer close to an

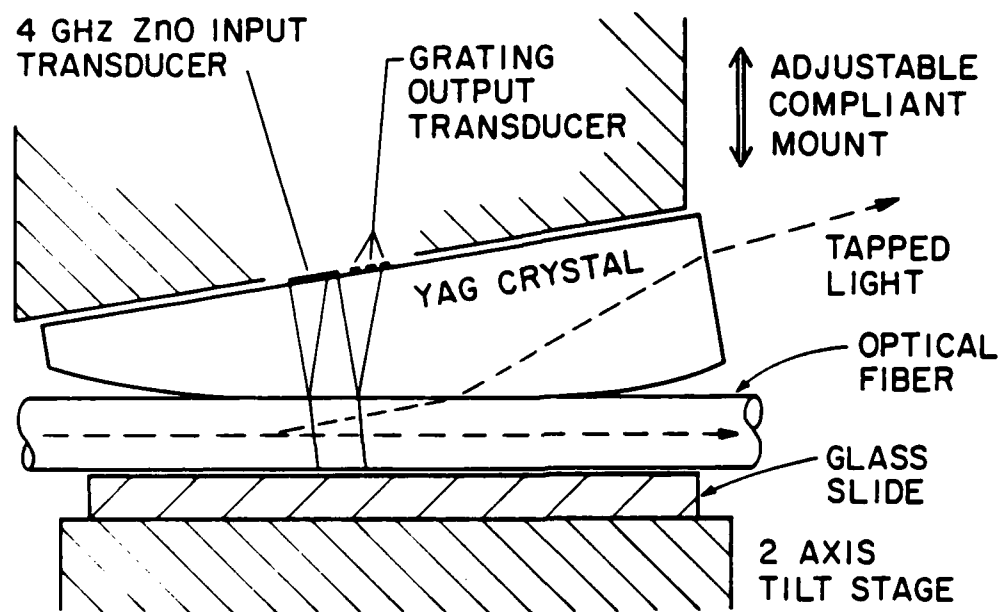


Fig. 1. Acousto-Optic fiber tap. Part of the acoustic beam is shown reflected to the output transducer. Light in the fiber is scattered upward by the Bragg interaction.

edge, we have developed a technique using special teflon clamps to spin photoresist usable to within 100 μm of the crystal edges. We have not yet made convolvers with two working input transducers, but our fabrication process continues to be refined. We have attempted to convolve a 3.5 GHz signal with its own acoustic reflection. The expected convolution output was observed along with other anomalous signals. The lack of a second input transducer made it impossible to fully explore these anomalous signals, but we are hoping for better results from a new set of 6 GHz convolvers which is nearing completion.

C. PUBLICATIONS, INVITED PAPERS, ORAL DISCLOSURES, PATENTS, AND HONORS/AWARDS/PRIZES

1. Publications

B. L. Heffner, G. S. Kino, and B. T. Khuri-Yakub, "7 GHz Acoustic Transmission Through a Hertzian Contact," Appl. Phys. Lett. (submitted for publication).

2. Invited Papers

"Measurement Techniques for Electronic Devices," DARPA/AF Review of Progress in Quantitative NDE, San Diego, CA (August 1984).

3. Oral Disclosures

None

4. Patents

None

5. Honors/Awards/Prizes

IEEE Sonics and Ultrasonics Group Achievement Award.

METAL-VACUUM-METAL TUNNELING OR
SCANNED TUNNELING MICROSCOPY

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A. INTRODUCTION AND OBJECTIVES

The interval covered by this report has been a period where we have initiated a new program of research in the physics and technology of surfaces. It is based on vacuum tunneling. We have spent much of our time in the design, fabrication and modification of systems that would allow us to study vacuum tunneling with our version of the STM (Scanning Tunneling Microscope). We have built several versions of the instrument; each a distinct improvement over the preceding models. With the operating instruments we have studied the surfaces of metals and semiconductors.

B. PROGRESS AND ACCOMPLISHMENTS

Related to our effort is the simultaneous effort in this field by a large number of research workers who are engaged in similar tasks. The most significant in the U.S. are those at IBM, Yorktown Heights, with R. Feenstra; at AT&T Bell Labs, Murray Hill, with J. Golovchenko; and at Ford Motor Company, Dearborn, with R. Jaklevic. In addition, a number of European laboratories are working in this field and this, of course, is dominated by the large effort in the IBM Research Lab near Zurich, where the original work was carried out. We have kept careful track of this effort through various meetings and personal contacts.

In December, a small group met in Cancun, Mexico, and spent several days reviewing our progress. In March, we convened a special symposium

at the American Physical Society Meeting in Baltimore and again reviewed the progress. In early July, we will meet in Europe for a full week of discussions to coordinate and plan for the future. And, later in July, a small group will meet at Stanford to discuss our own special set of problems.

It is clear from all of this that various people from a number of laboratories contribute significant bits and pieces that we incorporate into our system. From Zurich we have an improvement in the isolation system which is simplified over what we are now using. From Bell Labs, we find that tips can last for three weeks or more without degradation. From IBM (Yorktown), we find that cleaving GaAs produces a clean surface which gives high quality images. From Spain, we learn that carbon is a superior substrate which is small on an atomic scale over large areas.

We also have contributed with advances on our own. We have worked on the walker which is the device used to bring the sample into close proximity to the scanning tip. We have tried several variations with electrostatic clamping through thin dielectric layers. We have built magnetic systems with electromagnets to move the device. In the end we chose the magnetic system to enable us to reliably move the walker in two dimensions over great distances with very small steps. We have incorporated a heater into our system so that we can now use the walker to move the sample far from the tip and there heat it to a temperature of 900°C . While it is cooling we move it towards the tip to prepare for scanning. The entire combination is now working quite reliably and producing good images.

We have spent time on the scanners used to move the tip in three dimensions to cover the field of the image and maintain the proper spacing between the tip and the sample.

We have located a source of electrostrictive elements and have incorporated these in the scanner as a partial replacement of the piezoelectric elements. The electrostrictive elements have several advantages: they operate with a lower voltage for a given displacement, they are more linear and they do not creep after the application of a voltage pulse. These are important to the point where we expect that the electrostrictive elements will replace all elements in the scanner as we learn to shape them into our required forms.

The tip has demanded our attention since it is the most unreliable component in the entire system. Tip formation is still a black art and the experience of the entire community suggests that they have a short lifetime after formation. For our part, we are working with Lyn Swanson at the Oregon Graduate Center on the problem of forming tungsten tips which have the proper diameter and exhibit great stability. Swanson has experience with forming tips for field emission by heating them to a high temperature and "field evaporating" the surface atoms with a large electric field.

We have further improved our system for isolating the scanning instrument from external vibrations. We have followed up on a suggestion from the Zurich group and constructed an acoustic filter. This consists of a series of metal plates separated by Viton O-rings which act as the damping element. It seems to perform very well. It is more compact and more rugged than the system which relies on long springs and eddy current damping.

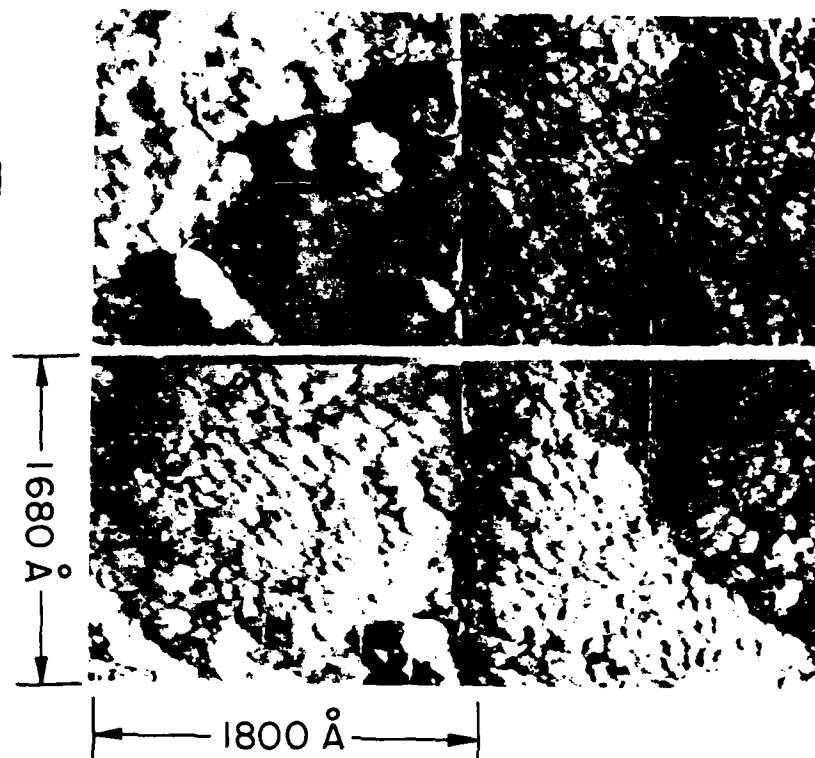
With the electronics we have also made contributions. In our system, where the image consists of 256 x 256 pixels, we generate, digitize and store an image in a time as short as 5 sec. This compares to several minutes in other laboratories.

With the images themselves we have made contributions with three materials: (1) a fine grained alloy of Cu-Ti, (2) a single crystal of platinum, and (3) the [100]-surface of silicon. The Cu-Ti alloy consists of fine grains - some 50 Å in diameter. An example is included as Fig. 1. Heretofore, these could only be viewed with the TEM (Transmission Electron Microscope) and this requires the tedious procedure of thinning the sample. The STM does not require the thinning operation and the resulting images have a larger contrast than do the TEM images.

With the [111]-surface of platinum we have been able to image atomic positions. The atoms are arranged in a two-dimensional array spaced several angstroms apart. This result represents the finest resolution that has been reported to date for the STM. We are pleased with this result since images from other labs show reconstructed surfaces where the spacing between atoms is larger than the bulk values.

With the [100]-surface of silicon we have been able to record images for both the surface before and after reconstruction. For this surface there is little difference in energy between several arrangements of the surface atoms and one should expect to see these on a given surface. This appears to be the case. We do observe small patches of different atomic arrangements and we are told that these results represent a distinct contribution to the field. They are now being written up and submitted for publication. Much of the material will appear in an issue of the IBM Journal for Research and Development, a special issue devoted entirely to vacuum tunneling.

(a)
STM



(b)
TEM

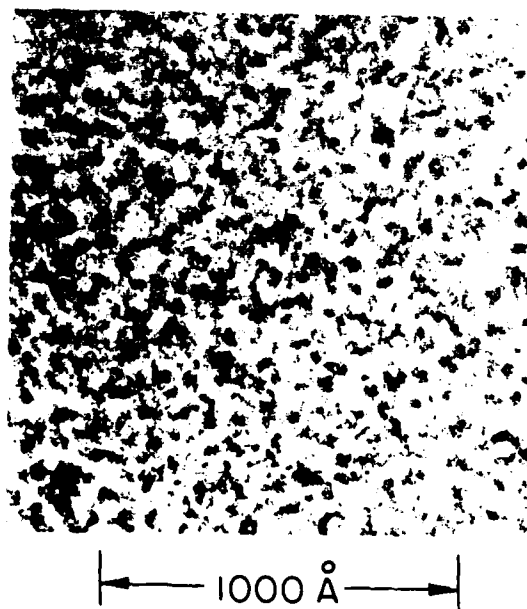


Fig. 1. Comparison between STM and TEM for copper-titanium.

C. PUBLICATIONS, INVITED PAPERS, ORAL DISCLOSURES, PATENTS, AND
HONORS/AWARDS/PRIZES

1. Publications

None

2. Invited Papers

"Modern Microscopy," Physics Department, University of California,
Santa Barbara, CA (October 2, 1984).

"Modern Microscopy," Electrical Engineering Department, University
of California, Irvine, CA (November 28, 1984).

3. Oral Disclosures

"Modern Microscopy," CIS Annual Review, Stanford University,
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"Progress in Vacuum Tunneling at Stanford," Workshop on Vacuum
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"Vacuum Tunneling," Post-Shrink Silicon Device Workshop, Semicon-
ductor Research Corporation, Chapel Hill, NC (January 10-11, 1985).

"Low Temperature Vacuum Tunneling Microscopy," Symposium of the
Division of Condensed Matter Physics: Tunneling Microscopy,
American Physical Society Meeting, Baltimore, MD (March 25-29,
1985).

4. Patents

None

5. Honors/Awards/Prizes

None

SECTION IV

Contract N00014-84-K-0327

Publications Activity

April 1984 - March 1985

Report No.		Contract, Grant or Sponsor
3752	Staff, Annual Progress Report, and Report of Significant Accomplishments (August 1984).	N00014-75-C-0632
3753	Staff, Final Technical Report, JSEP Final Report for 1 November 1974 to 31 March 1984 (July 1984).	N00014-75-C-0632
3754	M.M. Fejer, J.L. Nightingale, G.A. Magel, and R.L. Byers, "Laser Heated Miniature Pedestal Growth Apparatus for Single Crystal Optical Fibers," Rev.Sci.Instrum. 55(11), November 1984, pp 1791-1796.	N00014-75-C-0632 AFOSR-83-0193 DoE Subcont. LLL 8518101 NSF-DMR-80-20248
3838	B.L. Heffner, G.S. Kino, B.T. Khuri-Yakub, "7 GHz Acoustic Transmission Through a Hertzian Contact," Appl. Phys. Lett. 47(1) July 1985, pp 17-18.	N00014-84-K-0327
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SECTION V

Edward L. Ginzton Laboratory

Publications Activity

April 1984 - March 1985

Report No.		Contract, Grant or Sponsor
3709	G.S. Kino, J.D. Fox, and B.T. Khuri-Yakub, "Very High-Frequency Acoustic Transducers for Operation in Air," Preprint (April 1984).	DoE DE-AT03-81 ER10865
3710	B.T. Khuri-Yakub, "Low-Frequency Acoustic Microscopy," Progress Report for the period October 1983 through March 1984 (April 1984).	AMES SC-84-059
3711	Behzad Moslehi, Joseph W. Goodman, Moshe Tur and H.J. Shaw, "Fiber-Optic Lattice Signal Processing," Preprint (April 1984).	Litton Systems, Inc.
3712	A.E. Siegman, "Laser Physics and Laser Techniques," Final Scientific Report for the period 1 February 1982 to 31 January 1984 (April 1984).	AFOSR F49620-82-K-0015
3713	J.L. Brooks, R.C. Youngquist, G.S. Kino, and H.J. Shaw, "Active Polarization Coupler for Birefringent Fiber," Preprint (April 1984).	Litton Systems, Inc.
3714	B.Y. Kim and H.J. Shaw, "Gated Phase-Modulation Feedback Approach to Fiber-Optic Gyroscopes," Preprint (April 1984).	Litton Systems, Inc
3715	R.L. Byer, "Tunable Optical Sources," Final Report for the period 20 February 1981 to 19 February 1984 (April 1984).	DAAG29-81-K-0038
3716	B.A. Auld, "Elastic Domain Wall Waves in Ferroelectric Ceramics and Single Crystals," Annual Progress Report for the period 1 February 1983 through 31 January 1984 (April 1984).	N00014-79-C-0222

3717	D.E. Holmgren, D.J. Walker, D.A. King, and S.E. Harris, "Grotrian Diagram of the Quartet System of Na I," Preprint (April 1984).	F49620-83-C-0016
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3720	E.K. Gustafson and R.L. Byer, "Coherent Anti-Stokes Raman Scattering from Small Volumes," Preprint (April 1984).	NSF DMR-79-12673
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3722	Staff, "Superconducting Thin Films, Composites and Junctions," Interim Technical Report for the period 1 October 83 to 31 March 1984 (April 1984).	F49620-83-C-0014
3723	M.R. Beasley, "Supercon- ducting and Semiconducting Properties of Electron-Beam Evaporated Materials," Final Technical Report for the period 1 December 1975 to 31 October 1983 (April 1984).	DoE DE-AT0376ER71043
3724	R.M. Bradley and S. Doniach, "Quantum Fluctuations in Chains of Josephson Junctions," Preprint (May 1984).	NSF DMR-83-05723
3725	W.V. Soren, R.C. Youngquist, C.C. Cutler, and H.J. Shaw, "A Single-Mode Fiber Saturable Absorber," Preprint (May 1984).	Litton Systems, Inc.
3726	R. Enderlein and W.A. Harrison, "Solid-State Shifts of Core- Electron Binding Energies in Tetrahedral Semiconductors from Tight-Binding Theory, Preprint (May 1984).	NSF DMR-80-22365

3727	K. Bennett and R.L. Byer, "Optical Tomography: Experimental Verification of Noise Theory," Preprint (May 1984)	F49620-84-C-0021 DoE Subcont. LLL 3997405
3728	P.J.K. Wisoff and R.G. Caro, "A Superheated Na Cell for X-ray Photoionization Experiments," Preprint (May 1984).	N00014-78-C-0403
3729	D. Rugar and J.S. Foster, "Accurate Measurement of Low Energy Phonon Dispersion in Liquid (sup)4He," Preprint (May 1984).	N00014-77-C-0412
3731	B.T. Khuri-Yakub and G.S. Kino, "Effect of Photocarriers on Acoustic Wave Propagation for Measuring Carrier Density of Lifetimes in Silicon," Preprint (May 1984).	Schlumberger Inc.
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3736	W.P. Risk, R.C. Youngquist, G.S. Kino and H.J. Shaw, "Single Sideband Frequency Shifting in Birefringent Optical Fiber," Preprint (May 1984).	Litton Systems, Inc.
3737	B.Y. Kim, and H.J. Shaw, "A Phase-Reading, All-Fiber-Optic Gyroscope," Preprint (May 1985).	Litton Systems, Inc.
3738	B.Y. Kim and H.J. Shaw, "Gated Phase Modulation Approach to Fiber-Optic Gyroscope with Linearized Scale Factor," Preprint (May 1984).	Litton Systems, Inc.
3739	B. Auld, "Temperature Compensation of Surface Transverse Waves for Stable Oscillator Applications," Quarterly Report for the period 1 March to 31 May 1984 (June 1984).	F19628-83-K-0011
3740	K.E. Bennett, G.W. Faris, and R.L. Byer, "Experimental Optical Fan Beam Tomography," Preprint (June 1984).	F49620-84-C-0021

3741	Yuan Xuan Fan, R.C. Eckardt R.L. Byer, R. Route, and R.S. Feigelson, "AgGaS(sub)2 Infrared Parametric Oscillator," Preprint (June 1984).	DAAG29-81-K-0038 NASA NAG5-220
3742	M. Riazat, "Analytical Methods in Electromagnetic Nondestructive Evaluation," Internal Memorandum (June 1984).	EPRI RP1395-3 AMES SC-83-036 NBS 3015
3743	S.J. Bending, M.R. Beasley, and C.C. Tsuei, "Tunneling Study of Superconducting Al5 V-Ga Alloy Films, Preprint (June 1984).	N00014-83-K-0391
3644	G.S. Kino, "Research on Nondestructive Testing," Final Report for the period September 1979 to March 1984 (July 1984).	F49620-79-C-0217
3755	R.G. Caro, J.C. Wang, J.F. Young, and S.E. Harris, "X-Ray Excita- tion of Energetic Metastable Levels in Atoms and Ions", Preprint (July 1984).	N00014-78-C-0403 F49620-83-C-0016 DoE Subcont. LLL 3997405
3746	S. Elrod, A. deLozanne, and C.F. Quate, "Low Temperature Tunneling Microscopy," Preprint (July 1984).	NSF-DMR-80-20248 IBM #439514
3747	Staff, "Studies on Lithium and Sodium Metastable Quartet Atoms by Laser-Produced X-Rays," Progress Report for the period 1 February to 31 July 1984 (July 1984).	DoE Subcont. LLL 3997405
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3749	P. Broussard, D. Mael, T. Geballe, "The Specific Heat of Niobium- Zirconium Multilayers," Preprint (June 1984).	F49620-83-C-0014
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3752	Staff, Annual Progress Report, and Report of Significant Accomplishments (August 1984).	N00014-75-C-0632
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3754	M.M. Fejer, J.L. Nightingale, G.A. Magel, and R.L. Byers, "Laser Heated Miniature Pedestal Growth Apparatus for Single Crystal Optical Fibers," Preprint (July 1984).	N00014-75-C-0632 AFOSR-83-0193 DoE Subcont. LLL 8518101 NSF-DMR-80-20248
3755	B.M. Moslehi, "Fiber Optic Lattice Signal Processing," Internal Memorandum (August 1984).	Litton Systems, Inc.
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3757	K. Bennett, "Optical Tomography," Internal Memorandum (July 1984).	F49620-84-C-0021
3758	N. Read, D.M. News, and S. Doniach, "Stability of the Kondo Lattice in the Large -N Limit," Preprint (August 1984).	NSF PHY-77-27084 NSF DMR 80-07934
3759	C.C. Williams, "High Resolution Acousto-Optic Laser Probe," Preprint (August 1984).	AFOSR-82-0248
3760	J. Foster, "High Resolution Acoustic Microscopy in Superfluid Helium," Preprint (August 1984).	N00014-77-C-0412
3761	P.N. Strenski and S. Doniach, "On a System of Three Josephson Junctions," Preprint (August 1984).	NSF DMR-80-07934
3762	G.S. Kino, "Measurement Tech- niques for Electronic Devices," Invited Paper (August 1984).	F49620-79-C-0217 N00014-78-C-0283
3763	B.T. Khuri-Yakub and L.R. Clarke "Effects of Surface Residual Stress on Crack Behavior and Fracture Stress in Ceramics," Preprint (August 1984).	DoE-DE-AT03-83ER45020

3764	G.S. Kino and W.P. Risk, "Acoustic Modulators for Optical Fibers," Preprint (August 1984).	DoE DE-AT03-83ER45020
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3766	B.A. Auld, "Temperature Compens- ation of Surface Transverse Waves for Stable Oscillator Applications," Quarterly Report for the period 1 June to 31 August 1984 (August 1984).	F19628-83-K-0011
3767	R.L. Byer, "Growth and Evaluation of AgGaAs(sub)2 and AgGaSe(sub)2 Nonlinear Crystals," Final Report (November 1984).	SRI NASA Grant 5-220
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3769	J.L. Hall and T.W. Hansch, "External Dye Laser Frequency Stabilizer," Preprint (August 1984).	NSF PHY-83-08271 N00014-C-78-0403
3770	B.T. Khuri-Yakub, P.I. "Evaluation of Machining Damage in Brittle Materials," Final Report (September 1984).	DoE DE-AT03-83ER45020
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3772	B.H. Kolner, and D.M. Bloom, "Direct Electro-Optic Sampling of Transmission Line Signals Propagating on a GaAs Substrate," Preprint (August 1984).	IBM #429414
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3775	R.G. Stearns, B.T. Khuri-Yakub, and G.S. Kino, "Phase Modulated Photoacoustics," Preprint (August 1984).	N00014-78-C-0283
3776	R.M. Bradley and P.N. Strenski, "Directed Diffusion-Limited Aggregation on the Bethe Lattice," Preprint (September 1984).	NSF DMR-80-07934
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3778	S.E. Harris and J.F. Young, Studies on Production of Lithium and Sodium Metastable Quartet Atoms by Laser Produced X-Rays," Final Report for the period 1 October 1983 to 30 September 1984 (October 1984).	DoE Subcont. LLL 3997405
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3780	S. Doniach, "Theory of Cooperative Phenomena in Superfluid Systems of Reduced Dimensionality," Final Report for the period 1 July 1980 to 31 December 1983 (October 1984).	NSF-DMR 80-07934
3781	Rick Trebino, "The Achromatic N-Prism Beam Expander: Optical Configurations," Preprint (October 1984).	F49620-84-C-0041
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

AD-A158 840

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS										
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited										
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE												
4. PERFORMING ORGANIZATION REPORT NUMBER(S) G.L. # 3891		4. MONITORING ORGANIZATION REPORT NUMBER(S)										
6a. NAME OF PERFORMING ORGANIZATION Edward L. Ginzton Laboratory Stanford University	6b. OFFICE SYMBOL	7a. NAME OF MONITORING ORGANIZATION Joint Services Electronics Program (Through) Office of Naval Research										
6c. ADDRESS (City, State and ZIP Code) Stanford University Stanford, California 94305		7b. ADDRESS (City, State and ZIP Code) 800 North Quincy Street Arlington VA, 22217										
8a. FUNDING/SPONSORING ORGANIZATION Joint Services Electronics Program	8b. OFFICE SYMBOL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-84-K-0327										
8c. ADDRESS (City, State and ZIP Code) Dr. K.L. Davis 414 Head Electronics Division Office of Naval Research 800 North Quincy Street Arlington VA, 22217-5000		10. SOURCE OF FUNDING NOS. <table border="1"><tr><td>PROGRAM ELEMENT</td><td>PROJECT NO.</td><td>TASK NO.</td><td>WORK UNIT NO.</td></tr><tr><td></td><td></td><td></td><td></td></tr></table>		PROGRAM ELEMENT	PROJECT NO.	TASK NO.	WORK UNIT NO.					
PROGRAM ELEMENT	PROJECT NO.	TASK NO.	WORK UNIT NO.									
11. TITLE ANNUAL PROGRESS REPORT, 1 APRIL 1984 THROUGH 31 MARCH 1985												
12. PERSONAL AUTHORS S.E. Harris, D.M. Bloom, R.L. Byer, G.S. Kino and C.F. Quate												
13a. TYPE OF REPORT Annual Progress Report	13b. TIME COVERED From:04/01/84 To: 03/31/85	14. DATE OF REPORT (Yr Mo Day) 85 07 15	15. PAGE COUNT									
16. SUPPLEMENTARY NOTATION												
17. COSATI CODES <table border="1"><tr><th>FIELD</th><th>GROUP</th><th>SUB GROUP</th></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr></table>		FIELD	GROUP	SUB GROUP							18. SUBJECT TERMS (Continue on reverse if necessary & identify by block no.)	
FIELD	GROUP	SUB GROUP										
19. ABSTRACT (Continue on reverse if necessary & identify by block no.) This report is the Annual Progress Report for Joint Services Electronics Program Contract N00014-84-K-0327 for the Faculty of the Edward L. Ginzton Laboratory of Stanford University (S.E. Harris, Director). The report includes contributions on 4 Units: (Unit 85-1: Professor D.M. Bloom) Picosecond Optical Measurements; (Unit 85-2: Professor R.L. Byer) Optical and Nonlinear Optical Studies of Single Crystal Fibers; (Unit 85-3: Professor G.S. Kino) Very High Frequency Signal Processing Techniques; (Unit 85-4: Professor C.F. Quate) Metal-Vacuum-Metal Tunneling or Scanned Tunneling Microscopy.												
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED [X] SAME AS RPT [] OTIC USERS []		21. ABSTRACT SECURITY CLASSIFICATION Unclassified										
22a. NAME OF RESPONSIBLE INDIVIDUAL S.E. Harris, Director, Edward L. Ginzton Laboratory		22b. TELEPHONE NUMBER (415) 497-0224	22c. OFFICE SYMBOL									

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE (CONTINUATION)

18. SUBJECT TERMS (Continued)

19. ABSTRACT (Continued)

END

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10-85

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